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Sternberg, Saul

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This is the Annual Technical Report of work supported by a grant entitled "The dynamics of visual representation: Attention, encoding, and retrieval processes." After a section describing the objectives of the work, the report provides a synopsis of the principal accomplishments thus far, under the following headings: Relations between the transformation revealed by two paradigms, Influence of reciting direction on location-probe performance in the probed-reciting/location-probe mixture, Improvements in the timing of spoken responses, Representation of location information, Initial results from a double-location-probe procedure, Completion of analyses and publication supporting stages in mental operations, Effects of two kinds of degradation on encoding arrays of characters, and Effects of legibility on order of processing.

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Annual Technical Report

October 1, 1990 - September 30, 1991

1. Objectives.

We will conduct psychological research to investigate how visual information is represented in the human mind during the first few seconds after a display. We will investigate (1) how many representations exist, when they are available, and their properties, (2) how the transformation from one representation to another is accomplished, and (3) the mechanisms by which information in these representations is selected and retrieved. These issues will be investigated primarily by conducting behavioral experiments with human subjects, in which the principal measure is the time (reaction time, RT) a person requires to respond to a query of information that was present in the display. The experiments will use variations of four different paradigms:

(a) *Location Probe.* The probe, usually a visual marker (but sometimes tactile), specifies a location; the response is to name the item that is or was in that location.

(b) *Identity Probe.* The probe, usually a spoken name (but sometimes visual), specifies the identity of a target item; the response is to name the item in the array to the right of the target.

(c) *Probed Reciting.* The probe, a tone burst, specifies direction; the response is to recite the entire array in that direction.

(d) *Location-Specific Matching.* The probe is a visual *target* item that also marks the location of a *test* item within the array; the response is "yes" or "no", depending on whether target and test items match.

2. Principal Accomplishments

In our experimental work we have been concentrating on two general areas within the proposed research. The first is to investigate the location-probe (LP) and probed-reciting (PR) paradigms further, moving initially towards tests of whether the transformations that underlie the performance changes with probe delay in the two procedures are the same or different. The second has been to test new procedures for investigating other properties of early and late representations, especially the way in which location information is coded. In both domains there has been a good deal of software development, along with pilot experiments. A large formal experiment in the first area is in progress.

2.1 Relations between the transformations revealed by two paradigms. The method we have initially tested here is to compare performance in control conditions in which LP and PR paradigms are used separately, with an experimental LP-PR condition in which they are mixed under uncertainty, i.e., in which, on any trial, the subject sees an array [number of items (size) varied from trial to trial] and then, after a delay (varied from block to block), randomly either sees a location probe and responds with the name of a single item, or hears a tone and responds by naming all the items in sequence. If the two transformations are the same, then performance in the mixed condition should look the same as in the control conditions for both procedures at each probe delay, except possibly for an effect of mixing (and having to discriminate the two kinds of probe) on the intercepts of the functions that relate mean RT to array size. Results from pilot tests thus far indicate that subjects can handle the mixed task smoothly; we have discovered a difference, however, between LP (but not PR) performances in control and mixed conditions (mean RT in the LP condition increases substantially more with array size in the LP-PR mixture) indicating that the two transformations differ. The full experiment, now in progress, permits additional tests, in which we compare the transformation rates across subjects in the single-task control conditions, as assessed by changes in slopes of the RT versus array-size functions they generate (model free), and by fitting serial transformation models and using estimated rate parameters. If our finding is borne out, it raises the question, of course, of why the transformations differ.

Because the current experiment involved a mixture of two tasks in some conditions, the program to generate stimulus materials — here the displayed item sequences (and the probed location in the LP task) — was entirely rewritten. Because the design also called for balancing of up to 6 trial dimensions, the new program was complex (about 2000 lines of code in C). However, we regard this major effort as worthwhile, especially for experiments in which subjects are practiced for many days, partly because without adequate balancing they can learn to anticipate properties such as which of the two kinds of response will be required, or which location will be probed; it is critical for for success of the experiment that they be unable to anticipate such trial properties.

2.2 Influence of reciting direction on LP performance in the PR-LP mixture. We already know that the slope of the function that relates mean RT in the PR task to the number of digit items in a row is greater when reciting is from right to left (backwards) than forwards. This can be explained by the idea that the transformation process that precedes the vocal response depends on the direction that reciting will ultimately take, and, in particular, that the order in which array items are transformed is controlled by the order of reciting, and is hence under experimental control. If this is so, then whether or not the LP and PR transformations are the same, we might see an effect of reciting direction on LP (non-reciting) trials that are mixed randomly with PR trials in the LP-PR mixture, at intermediate delays. (At such delays, only items early in the reciting order would have been transformed, and a transformed item might produce a faster LP response.) Thus the LP performance might serve as a sensitive indicator of the transformation state of individual items. Indeed we found such an effect when we compared the slopes of the serial-position curves for LP trials in LP-PR blocks in which reciting direction was always either forward or backward. To eliminate biases in eye position as a cause, we developed a procedure in which the required reciting direction was varied randomly from trial to trial, signalled by a salient visual cue concurrently with the brief display; the effect on LP trials was the same. Finally, if the transformation time per item is increased (by degradation of the array) we expected the left-to-right differential to increase on LP trials, and found indeed that it did. A formal experiment to test for an influence of reciting direction on LP performance in the PR-LP mixture is planned for December, using subjects currently being trained in the mixture condition.

2.3. Improvements in the timing of spoken responses. We have devoted a good deal of effort to improving the precision of our measures of vocal response latency and duration. The most significant of several modifications of the experiment-running code is the addition of storage of detailed records of subject utterances in a form that permits rapid analysis. In the past, we have filtered the speech in high-frequency and low-frequency bands, and the energy in each of these bands has been measured for each 10-msec epoch. A threshold has been applied in each band, and the utterance is deemed to have started when the first run of specified length of 10-msec epochs is detected. A similar decision rule has been used for determining when the utterance ends. (We have also stored a measure of peak level in each band.) However, this method requires us to commit ourselves to particular values of threshold and run length before the experiment, rather than adjusting these parameters to particular subjects, based on characteristics of their speech. The alternative of storing a complete digital record of the speech at a sampling rate of, say, 10kHz, would consume too much space. The compromise we selected is to store the energy levels in each 10 msec epoch for each of the two bands. This record will allow us optimally to determine what parameters to use within our speech timing algorithm.

2.4. Representation of location information. A possibility that has been discussed a great deal is that one difference between early and later representations of visual information is in the coordinate system to which it is referred, with absolute or retinotopic coordinates early, and relative or spatiotopic coordinates later. In earlier work using the LP procedure we showed that the direct-access property found for the early representation is convincingly demonstrated by both tactile and visual probes. This might seem to suggest that direct access is not contingent on the use of absolute coordinates, but the result is not decisive for this conclusion, since it is possible that the response to a *tactile* probe is mediated by *absolute visual location* early, and by *relative visual location* later. Our principal new approach to this problem is to probe for an item by specifying its absolute versus relative location at different delays. In the LP procedure as used to date, the probe combines both kinds of information. Absolute location is represented by the relation between the probe and the fixation point; Relative location is represented by the relation between the probe and the registration marks which appear with the array, above and below each occupied location, and remain until the response. In a relative-location variant, the registration marks are removed, and then reappear in a (possibly) different set of contiguous absolute locations, along with the probe. In an absolute-location variant, the registration marks do not reappear, so the probe can be interpreted only by using its location in absolute space, relative to the fixation point. Much to our surprise, preliminary results indicate that after practice the slope of the function relating mean RT to array size is invariant over these three procedures. There is, however, an intercept difference, whose interpretation has to be considered: If computations were required to get from one coordinate system to another, but their duration was independent of array size, then they would be hard to detect with our method.) The suggestion from these initial data, however, is that at long

delays, relative and absolute location are equally useful as retrieval cues. Although detailed examination of the data patterns provides no basis for suspecting an effect of probe type on the kind of representation that is formed, we hope to guard against this by mixing the three kinds of probe within the same trial series. A formal experiment will be conducted during December, using subjects currently being trained.

2.5 Initial results from a double-LP procedure. One approach that may help clarify the change in retrieval mechanism in the LP procedure is to present two probes, simultaneously or with a small delay, and require a pair of responses, giving the spoken names of the items in the two positions probed. Of special interest is a *proximity effect*, the effect of the spatial separation of the two probes on the increment in retrieval time associated with the second item retrieved, which perhaps incorporates a "shift of attention" from the first location accessed to the second. We developed the software for such a procedure and began data collection, with very promising results. It would be consistent with inferences from our earlier findings with a single probe (and the idea of direct access by spatial position) if the proximity effect was relatively small when the pair of probes was presented close in time to the array; this property of the representation might change as the pair of probes is delayed, with the delay providing time for the transformation being studied to proceed. This is exactly what we found: The two probes were separated by 100 msec., and the array contained six items. When the first probe was presented 50 msec before array onset, there was essentially no effect of spatial proximity: the average effect of increasing the separation by one item was only 1 msec. When the first probe was presented 650 msec after array onset, the RT increased by about 28 msec for each item between the two items probed, a large effect, and a large difference as caused by the probe delay. We found similar effects, but less orderly ones, when the two probes were presented simultaneously. If these findings hold up then we may have learned something important about the differences between initial and later representations of visual information. A more formal experiment will be conducted toward the end of November. One important feature of this finding flows from the fact that it is not a change, with probe delay, in the effect of the *size* of an array, as are many of the effects we have been studying. Interpretation of such array-size effects requires one to consider the possible effects of an increase with delay in the dependence of memory load on array size, as well as the possibilities that interest us more: a change in basic properties of the visual representation. The proximity effect is measured with a fixed array size, so its increase with delay cannot be explained in this way, which facilitates its interpretation.

2.6. Completion of analyses and publication supporting stages in mental operations. Basic to the use of RT data in our ongoing studies of visual representation is the assumption that differences in RT as one varies the size of an array, for example, reflect differences in just the encoding and retrieval operations between probe and response, and don't depend on details of the process by which the response is executed, for example. The simplest circumstances that justify such an assumption are those in which the processes between probe and response are organized into distinct stages, with one stage beginning when and only when the prior stage ends. An important source of evidence for such a stage mechanism over the past two decades has been the finding of additive effects of experimental factors on mean RT. In recent years the stage model has been challenged, and it has been shown that there are other mechanisms that can also produce additive factor effects on the mean. This problem led to the development and application of some new tests, described in Publication (1), recently completed. One of the four experiments to which these tests were applied (a flash-detection experiment) is one in which the allocation of attention over visual space was investigated, bringing the work close substantively, as well as methodologically, to issues that are central to our research objectives. The work can be summarized as follows:

Additivity of the effects of experimental manipulations on mean RT has been taken to suggest that the underlying mechanism can be divided into independently changeable, serially arranged operations (Stage Model, additive-factor method; Sternberg, 1969). A similar conclusion has been drawn by Roberts (1987) from the many instances of multiplicative effects of experimental manipulations on response rate in animal experiments. In this paper we consider two other explanations of the same additive pattern of mean RTs: a model with independently changeable alternate pathways, and the McClelland-Ashby Cascade Model. In all three models, additivity reflects selectivity of the influence of experimental factors on mental operations. Among the new tests described are comparisons of entire RT distributions. Applied to the results of four diverse experiments (overlapping tasks, classification, identification, and detection), analyses of distributions and variances support the Stage Model and contradict the Cascade

and Alternate-Pathways models. One set of distributional analyses, based on a suggestion by Ashby and Townsend (1980), supports the Stage Model remarkably well.

Thus far five experts have read and commented on a preprint of the article; their comments included: "very important," "beautiful," "a wonderful contribution," "like a fine piece of art," and "very impressive." The most important part of this work will also be reported in Publication (4).

2.7. *Effects of two kinds of degradation on encoding arrays of characters.* Teresa Pantzer (a fourth-year graduate student) and I have been engaged in further analysis of the effects of two kinds of degradation on data from the PR paradigm and in a paradigm devised and studied by Pashler & Badgio (1985) (JEP:HPP, 11, 105-121) in which array-size effects are studied, also under conditions that seem to require that all array items be encoded before response initiation. The two kinds of degradation are superimposition of a grid (pattern mask, PM), and rotation and reflection of the character (RR). The effects these two kinds of degradation have on the function that relates mean utterance latency to array size are dramatically different, with PM influencing primarily the intercept, and RR influencing primarily the slope. This in turn suggests that PM affects a part of the encoding process (such as contour formation) that occurs in parallel over the visual field, whereas RR affects a part of the process (such as identification) that occurs serially, item by item. This work will be reported in Publication (2), recently drafted.

2.8. *Effects of legibility on order of processing.* One possibility that has never been seriously tested, to our knowledge, is that the relative legibility of displayed items has an effect on the order in which they are searched (in a search task) or otherwise processed. This is clearly important in studies such as the one described in Section 2.7 above, in which legibility is explicitly manipulated. With Peter Marvit, a first-year graduate student, I have begun planning some experiments to investigate this question, using the same two kinds of degradation to manipulate legibility as in the study described above. It seems possible that PM will influence processing order while RR will not, just because PM influences a parallel component of the encoding process that precedes and influences a serial component, whereas RR controls a serial component that requires an advance commitment to order.

3. Publications

In press:

(1) Roberts, S., & Sternberg, S.
The meaning of additive reaction-time effects: Tests of three alternatives.
In D. E. Meyer & S. Kornblum (Eds.) *Attention and Performance XIV.* MIT Press.

In draft form:

(2) Pantzer, T., Sternberg, S. & Lubin, J.
Serial and parallel encoding components: Evidence from effects of two kinds of visual degradation on whole report.
Likely journal: *Journal of Experimental Psychology: Human Perception and Performance.*

(3) Sternberg, S., Knoll, R. L., & Turock, D. L.
Short-term dynamics of visual representation: Direct access by spatial position.
Likely journal: *Journal of Experimental Psychology: Human Perception and Performance.*

In preparation:

(4) Sternberg, S., & Roberts, S.
New evidence from reaction-time tasks for stages in mental operations. Likely journal: *Science.*

4. Principal Personnel

(1) Ross W. Porter (Analyst/Programmer)
(2) Teresa Pantzer (4th-year graduate student, psychology)
(3) Peter Marvit (1st-year graduate student, psychology)
(4) Saul Sternberg (Principal investigator)